

Early Mission Maneuver Operations for the Deep Space Climate Observatory

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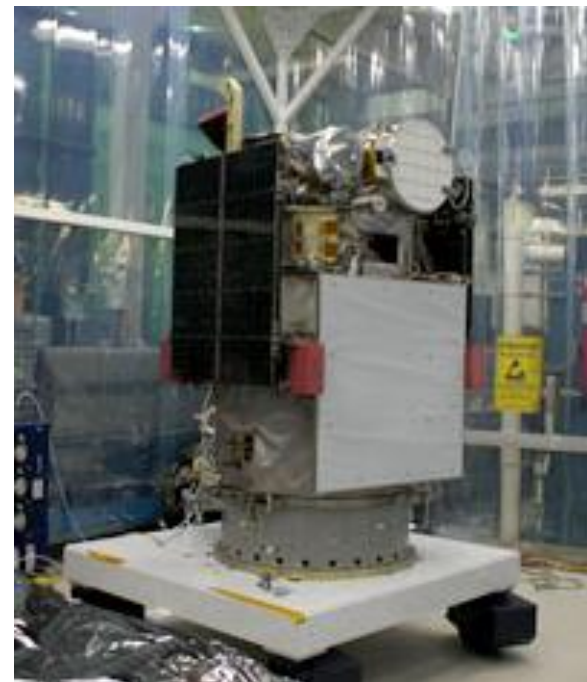
Introduction

- The Deep Space Climate Observatory launched on Feb 11, 2015 onto a libration point transfer orbit and completed its libration orbit insertion maneuver at the Sun/Earth L1 point on June 7, 2015
- DSCOVR orbits in a Lissajous about this unstable equilibrium point about 1.5 million km from Earth
 - About 1% of the way from the Earth to the Sun
- This presentation provides an overview of the mission, the trajectory, and the early orbit maneuver planning and analysis

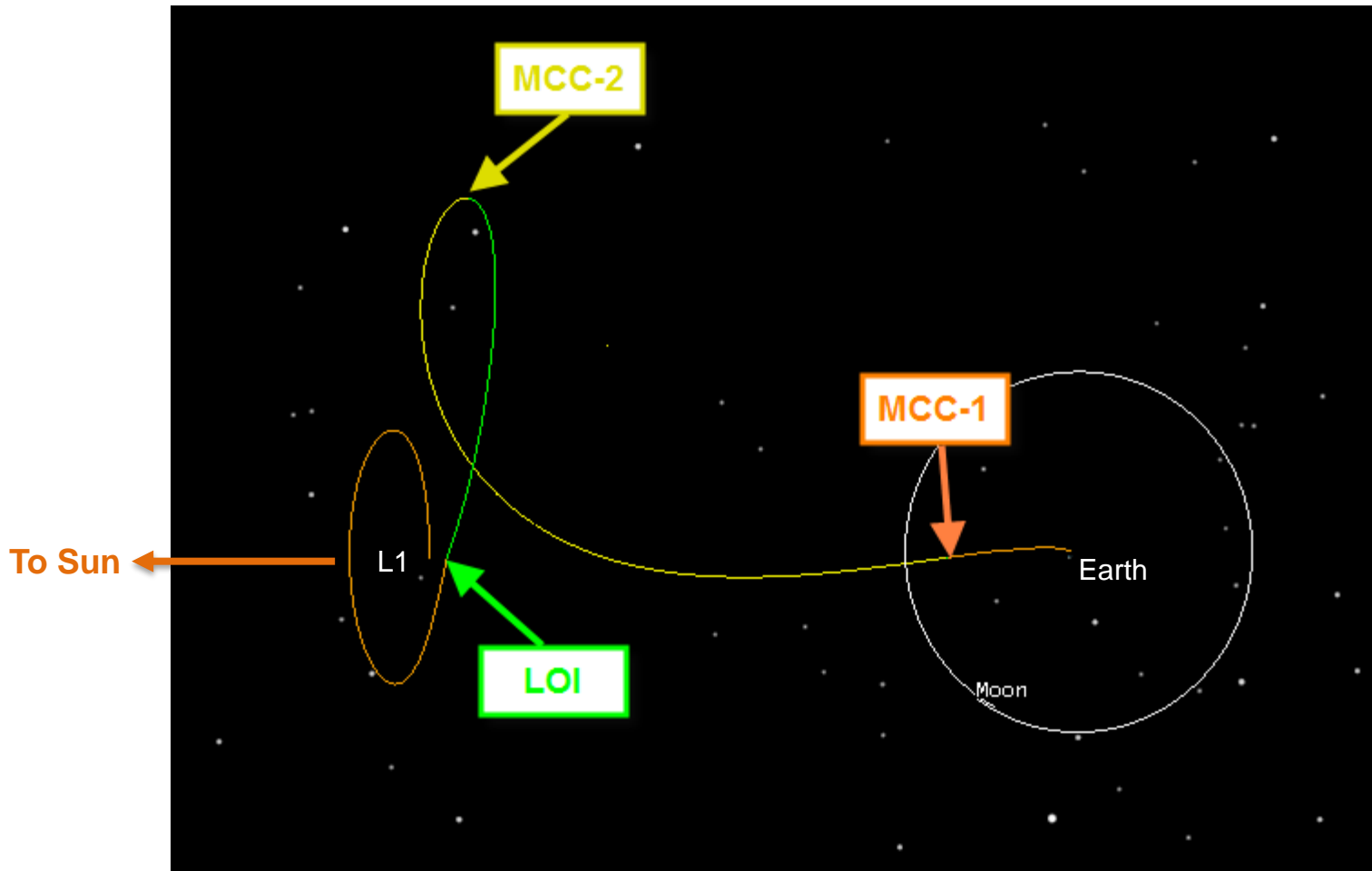


A Bit of History

- DSCOVR is a joint mission for NASA, NOAA, and USAF
- The mission was originally proposed as “Triana” and advocated by Al Gore as an Earth imager
- After being placed on hold in 2001, the satellite was in storage until 2008
- Repurposed as a follow-on to the ACE mission, which has been operating for over 17 years
- Primary DSCOVR objective is now space weather: solar wind measurement and early warning for solar storms
- NASA team completed hardware, software, and ground system refurbishment and testing
- Handover to NOAA in summer 2015

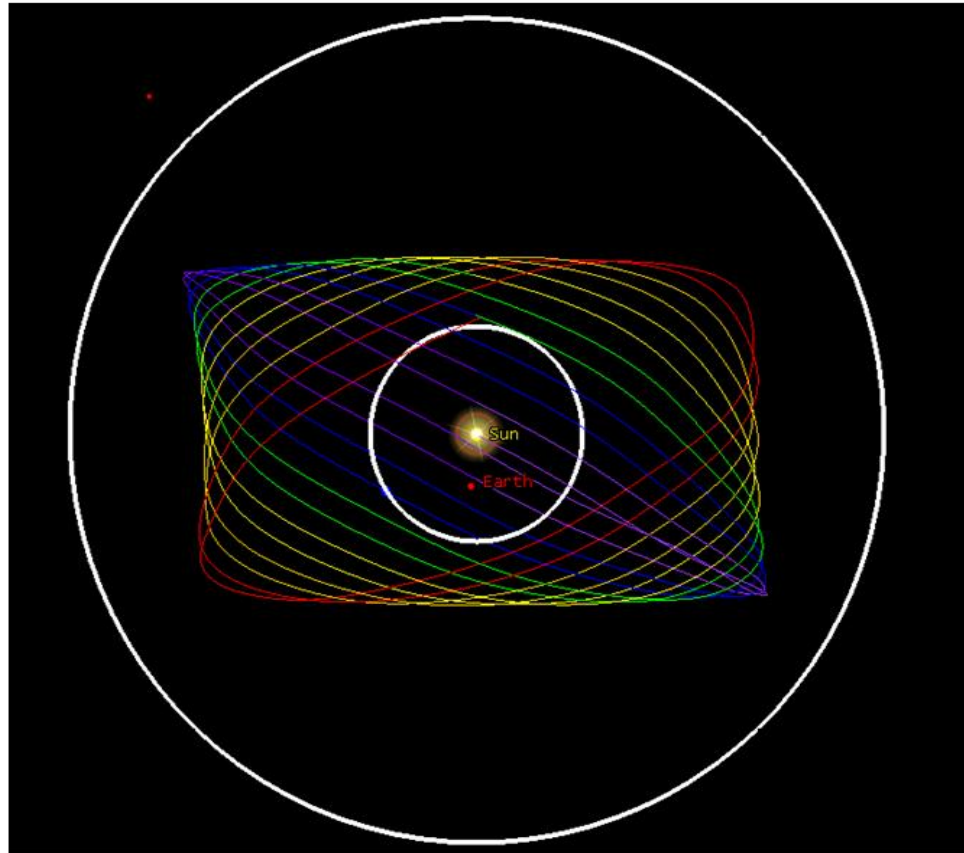


DSCOVR Trajectory and Maneuver Types (1/2)



- Mid-course corrections (MCC-1 and MCC-2)
- Libration Orbit Insertion (LOI)

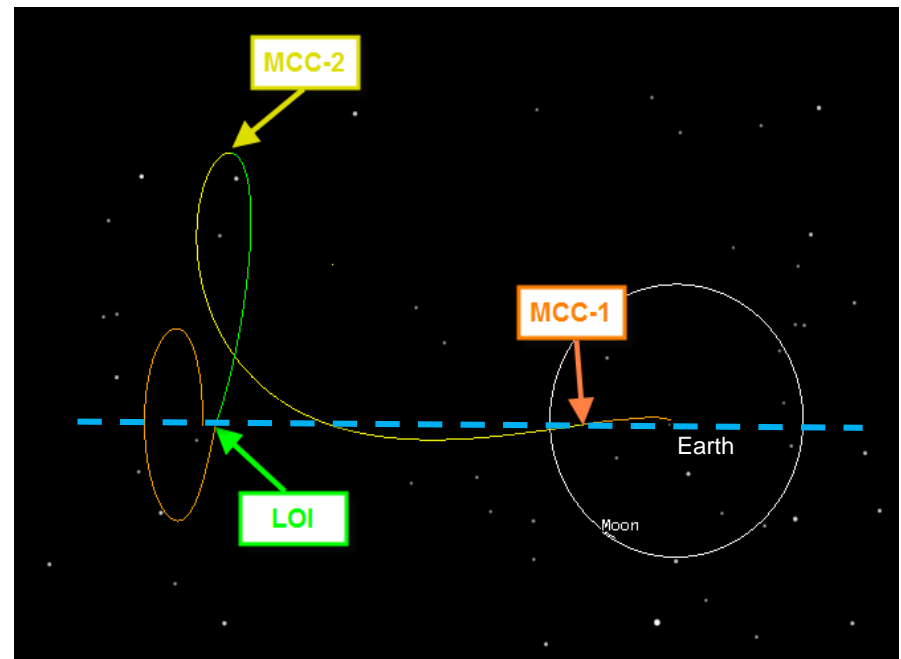
DSCOVR Trajectory and Maneuver Types (2/2)



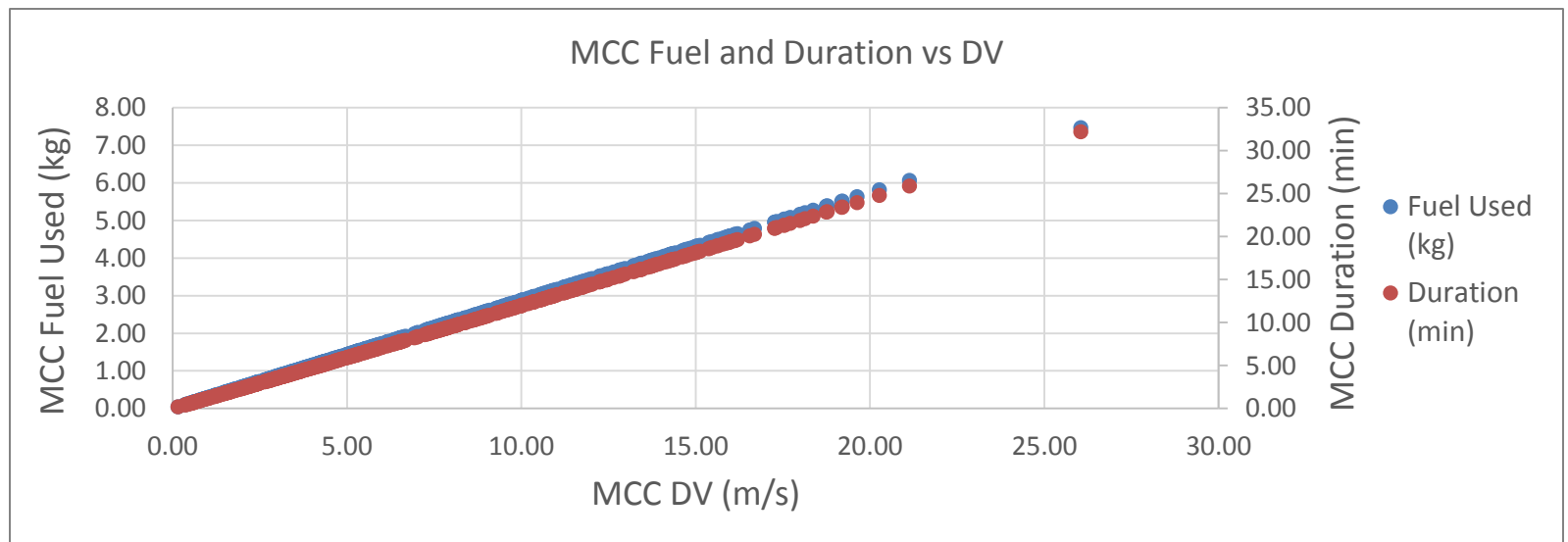
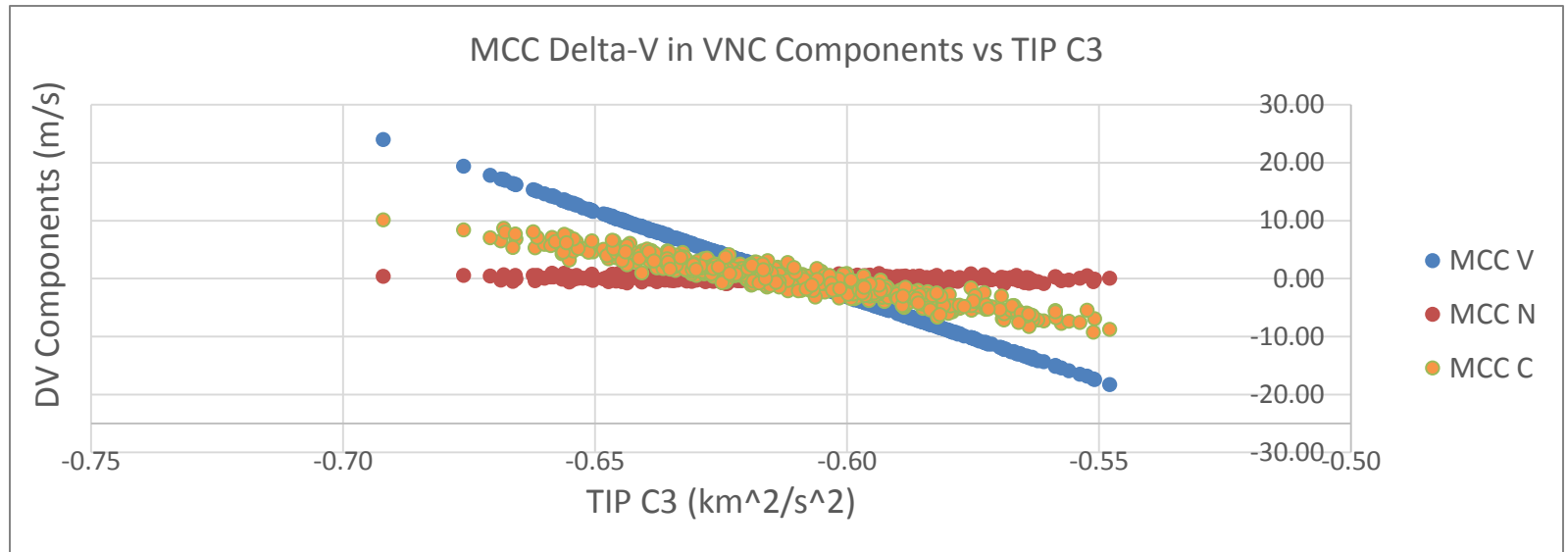
- Stationkeeping Maneuvers
- Solar Exclusion Zone Avoidance (SEZ)
- Will be discussed in detail in the next talk!

Launch and MCC-1

- The SpaceX Falcon 9 second stage injected DSCOVR directly onto the L1 transfer orbit
- SpaceX provided ~500 Monte Carlo launch vehicle dispersion cases for each launch date
- MCC planning software must be able to compute the correction for any dispersion
 - Short analysis timeframe immediately after launch
 - Want to avoid manual tuning of the differential corrector

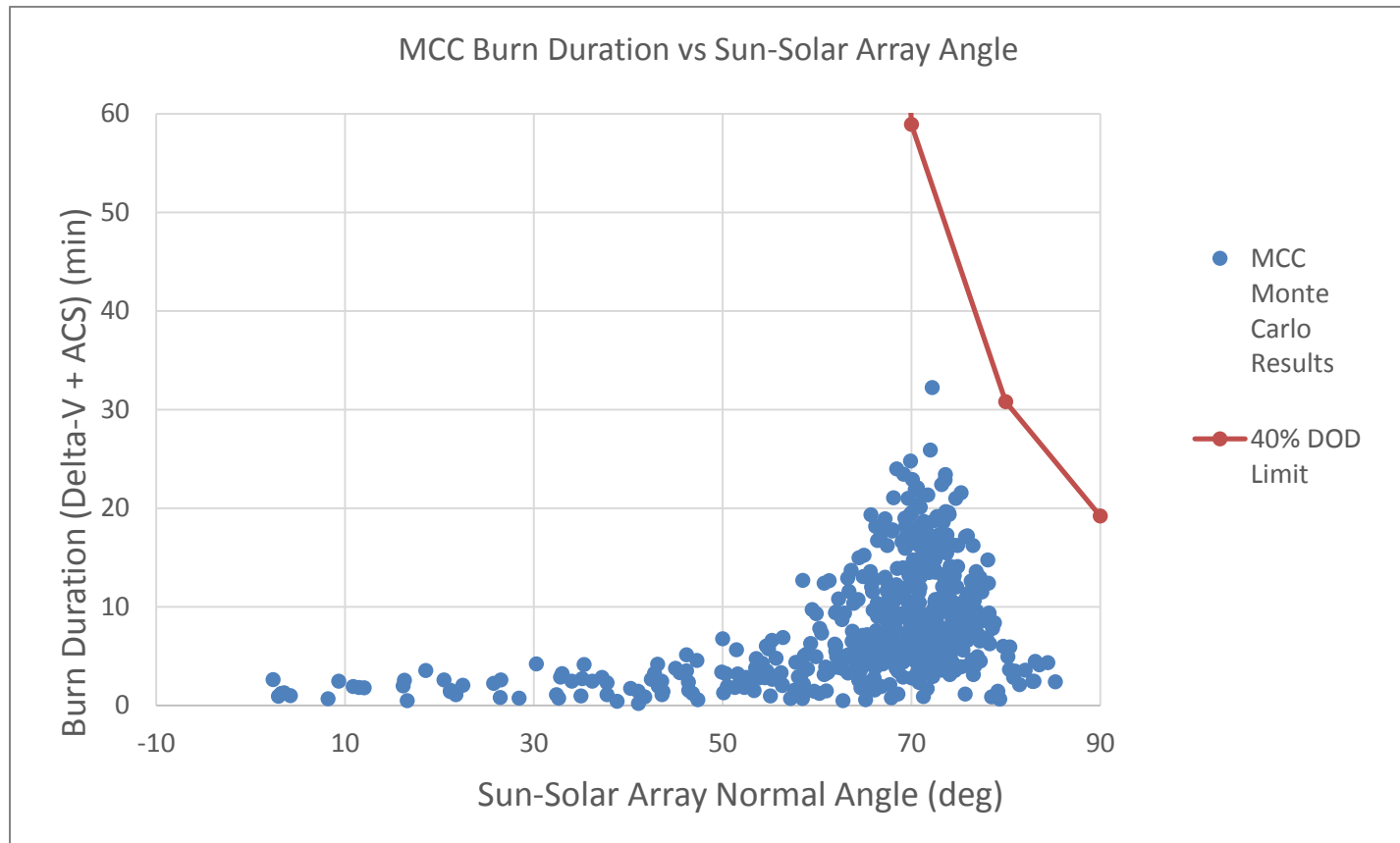


MCC-1 Monte Carlo Results



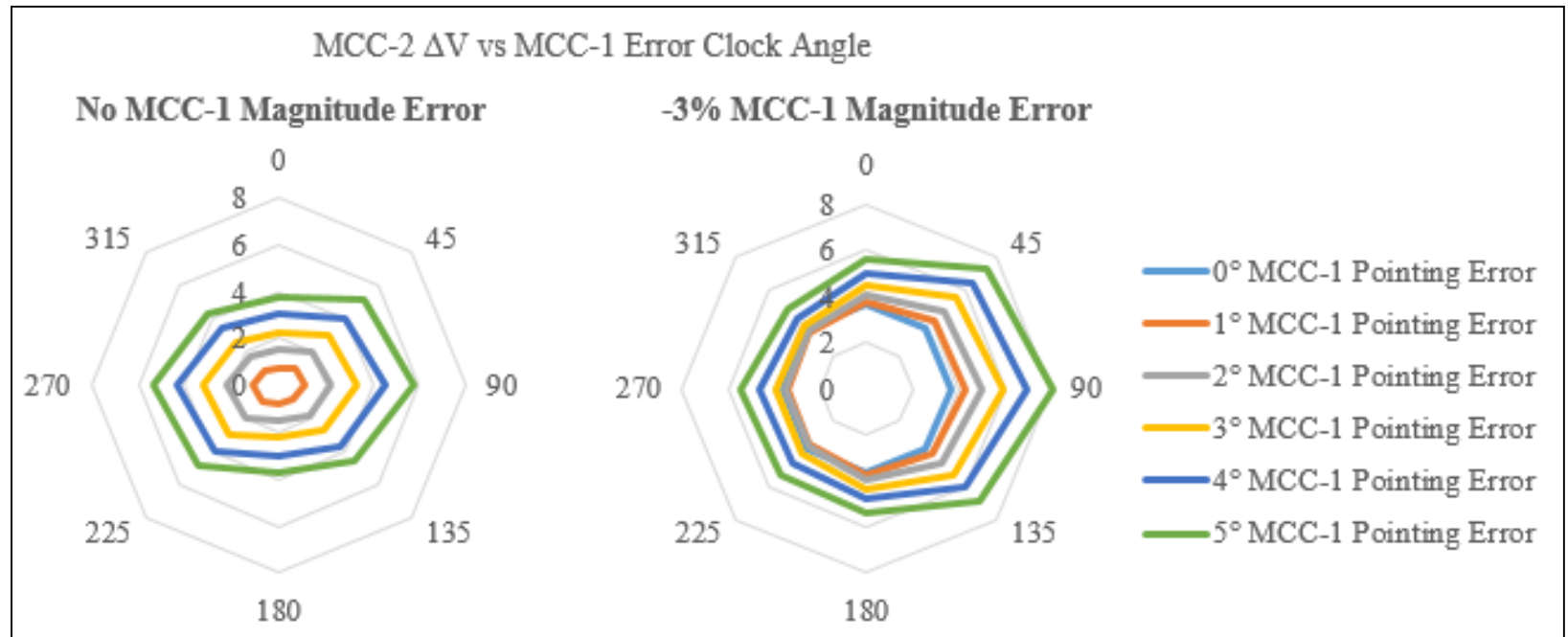
MCC-1 Power Constraints

- MCC-1 requires a pitch-over for a majority of launch cases
- Analysis to determine whether power constraints could require a segmented MCC-1 maneuver



MCC-1 Execution Error Analysis

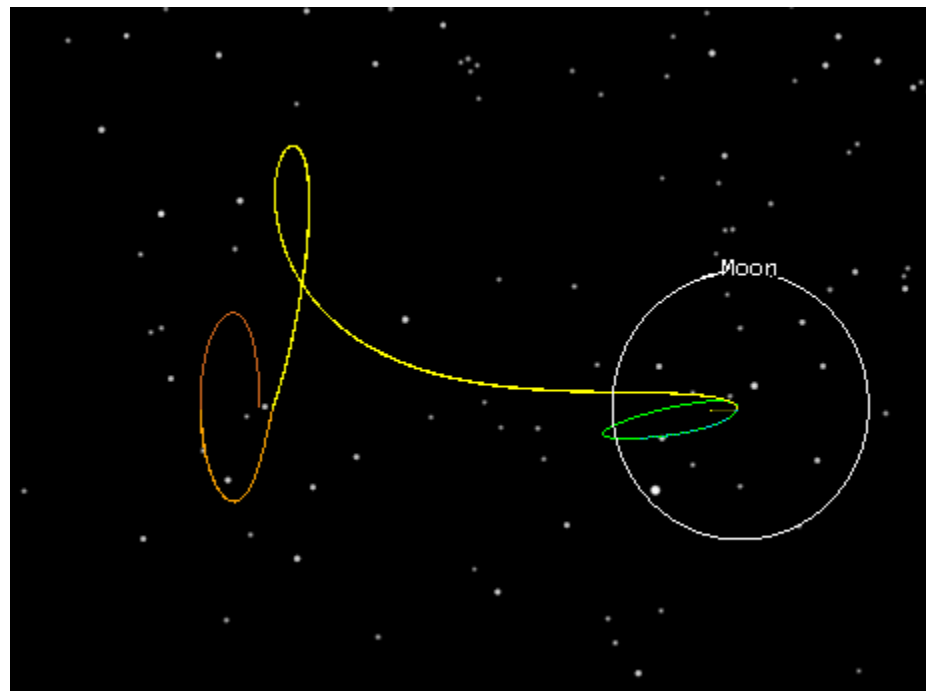
- Before flight, propulsion and attitude control teams provided a range of potential maneuver errors
 - Thrust models within 3%
 - Pointing requirement within 5°
- Analysis of possible MCC-1 errors and effect on MCC-2



Launch Anomaly Recovery

- First deep space launch for SpaceX...
 - What if we have a significant launch anomaly?
- In that case, the baseline plan to execute MCC-1 at about L+24 hours is not wise
 - The cost to correct an error at L+24 is about 6x the launch error
 - A 3σ underburn (4.5 m/s) would cost 27 m/s to correct at L+24
 - A 1% second stage underburn (32 m/s) would cost 192 m/s to correct at L+24
- Alternate recovery approach is to remain in a highly elliptical Earth orbit and execute the transfer insertion upon return to perigee
 - Requires a perigee raise maneuver
 - A plane change maneuver
 - An energy correction (transfer insertion) maneuver

Launch Anomaly Recovery Results



Underburn	Apogee Radius	Perigee Raise	Plane Change	Energy Correction	Cost of Recovery	Naïve MCC Cost
35 m/s	90 R _E	23 m/s	12 m/s	46 m/s	81 m/s	210 m/s
68 m/s	60 R _E	27 m/s	14 m/s	76 m/s	117 m/s	408 m/s
170 m/s	30 R _E	25 m/s	1 m/s	186 m/s	212 m/s	1020 m/s

MCC-1 Actual Results

- The Falcon 9 performance was wonderful
- Less than 0.2 sigma dispersion
- MCC-1 burn duration was 36 seconds
- Could certainly have waited weeks to perform MCC-1 without exceeding fuel budget
 - Executed as planned at L+24 hours to exercise prop system and avoid changing staffing and ground tracking plan

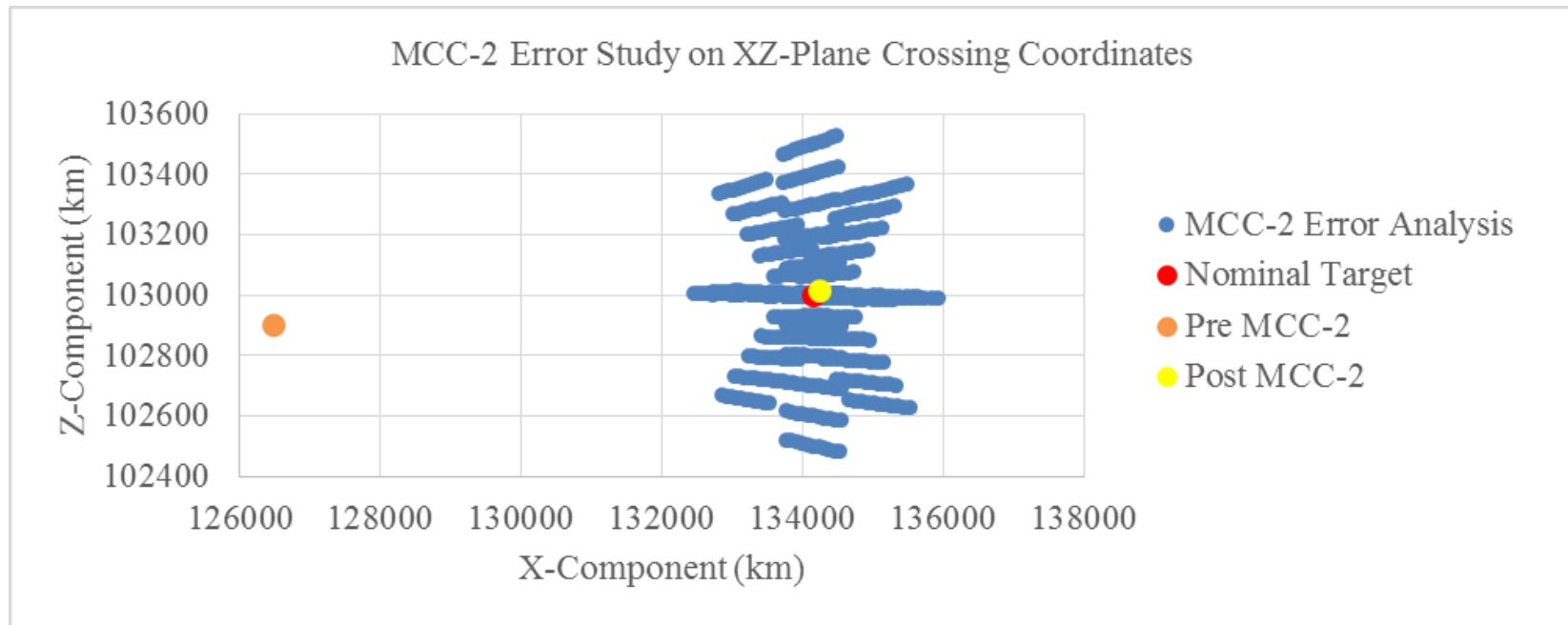


MCC-2 Planning

- Pre-flight expectation was to conduct MCC-2 three weeks after launch
 - Smooth execution of injection and MCC-1 allowed us to postpone until L+10 weeks
 - Longer maneuver was desired to provide confirmation of thruster calibration before the large LOI maneuver
- Nominal MCC maneuver targeting procedure found a solution which placed the spacecraft into an omni-antenna null region
- Customized targeter by constraining cross-track-component of the maneuver to zero to find a new solution
- Burn duration was 3 minutes (2.5 m/s ΔV)

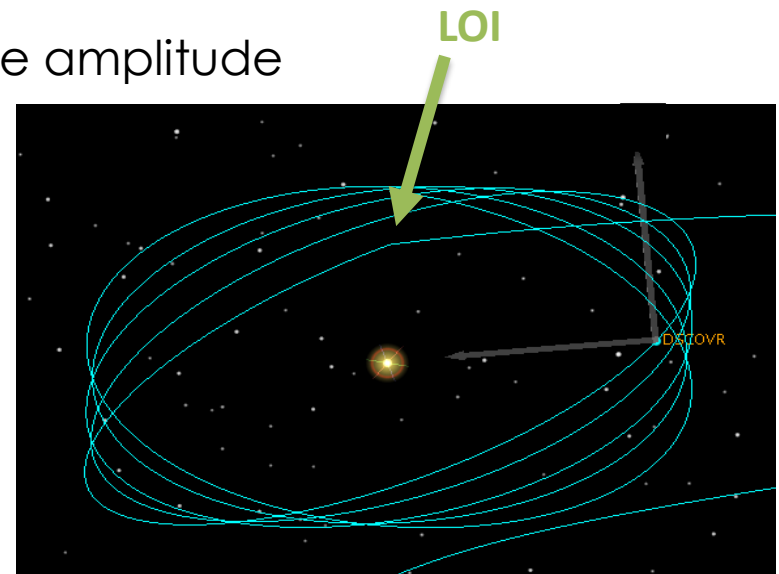
MCC-2 Execution Error Analysis

- Returning to range of potential maneuver errors
 - Analyzed thrust models variations up to 5%
 - Pointing variations up to 5°
- Analysis of possible MCC-2 errors and effect on RLP XZ plane crossing point



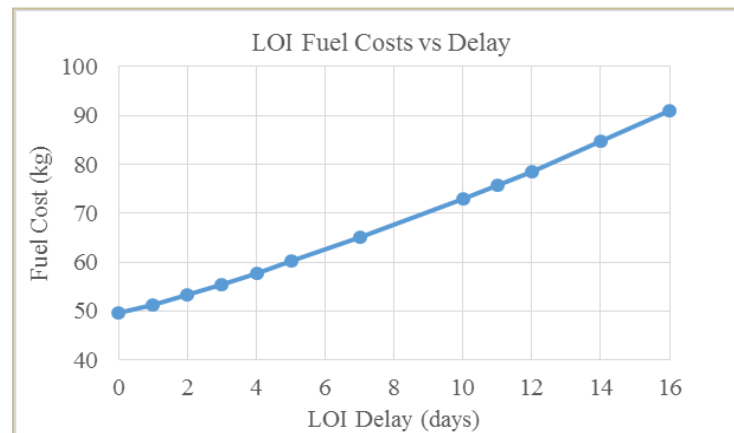
Libration Orbit Insertion

- The LOI maneuver bleeds off orbital energy and turns the trajectory to capture into an L1 libration point orbit
 - 166 m/s ΔV
 - 3:41 hours of ΔV thrusting with two 1-lb axial thrusters
 - 4:23 hours of total burn time (including attitude control thrusting)
 - 48.6 kg of fuel usage (33% of BOL fuel mass)
 - Lissajous orbit dimensions
 - 6° out-of-plane by 10° in-plane amplitude
 - 160,538 km by 281,476 km
 - Orbit “period” of approximately 6 months



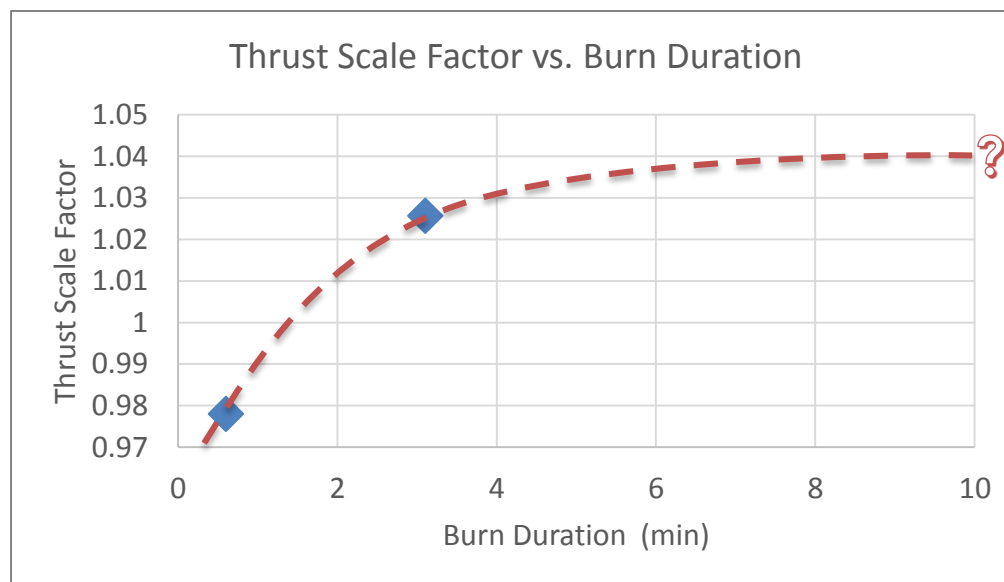
LOI Delay Cost Analysis

- Optimal LOI maneuver is executed in close proximity to the RLP XZ plane
- Identified significant costs associated with LOI execution delay over 4-5 days
 - LOI execution delayed more than 7 days introduces severe distortion of the Lissajous orbit
 - Would require a Lissajous reshaping burn at the next RLP XZ plane crossing to correct orbit back to the baseline design, substantially increasing cost and operational complexity



Thrust Scale Factor Calibration

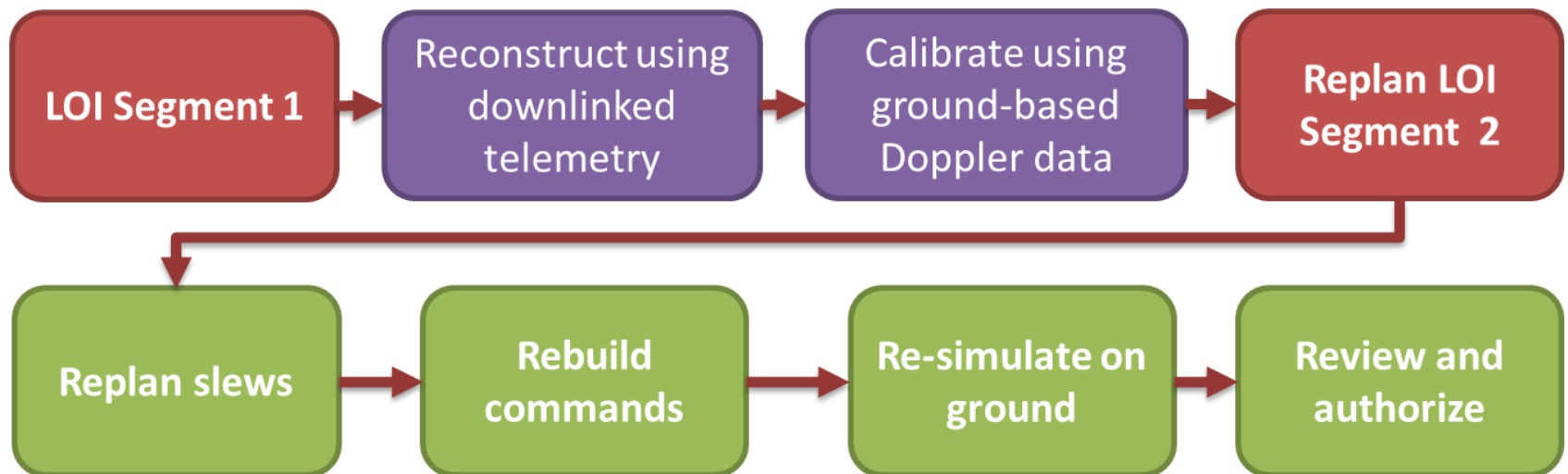
- We expect thrust scale factor to be a function of burn duration
- Unfortunately the calibration data points from MCC-1 and MCC-2 disagreed by nearly 5%



- A 5% error in LOI execution would affect the shape of the Lissajous orbit
 - Affects the mission Sun-Earth-Vehicle angle requirement
 - Would require a correction maneuver as soon as possible

LOI Segmentation Strategy (1/3)

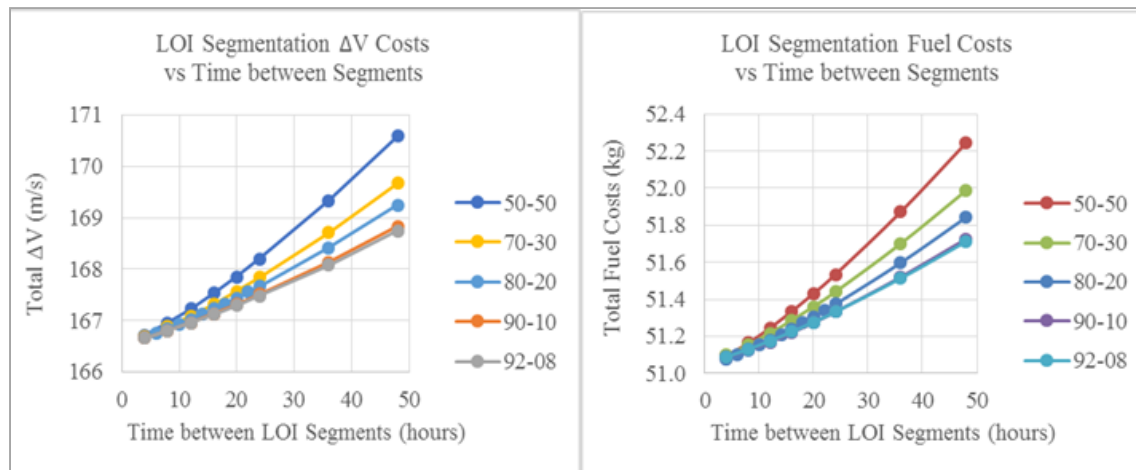
- LOI Segmentation allows us to recalibrate the thruster efficiency partway through the large maneuver
 - Reduces the expected cost of the LOI correction maneuver
 - But we don't want to delay completion of the insertion any longer than necessary



- All within 6 hours
 - Using exact same maneuver attitude (quaternion) for both segments to reduce time required for re-plan and review

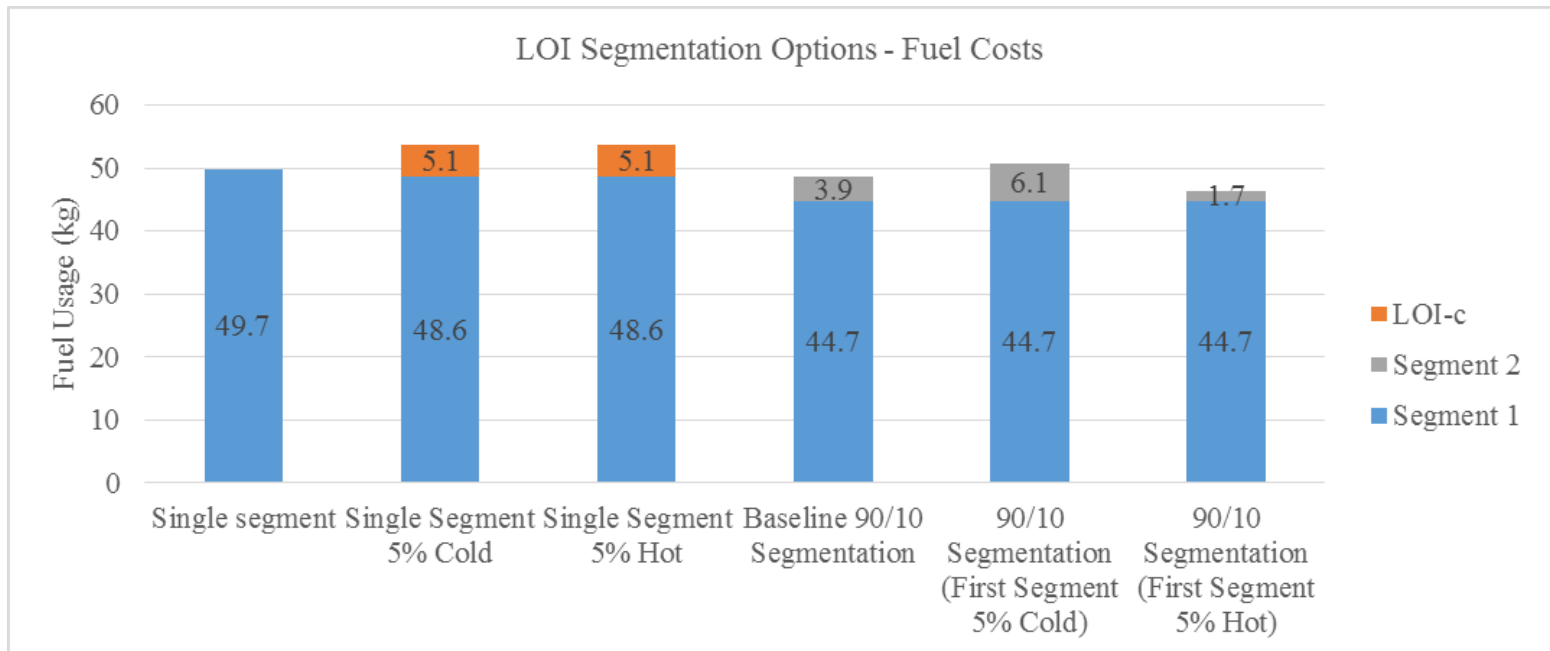
LOI Segmentation Strategy (2/3)

- Analysis of various LOI segment split ratios and duration between segments
- Decision drivers:
 - Want to complete majority of maneuver in Segment 1 in case of unexpected delay before Segment 2
 - Need Segment 2 to be long enough that thruster calibration data point from Segment 1 is applicable
 - Want to complete entire maneuver as close to the XZ plane crossing as possible
- Selection: 90/10 split ratio with 6 hours between segments



LOI Segmentation Strategy (3/3)

- Segmentation approach allows second segment to be re-planned to compensate for overburn/underburn of first segment right away
- Single-segment LOI approach would require us to wait 3 weeks until the LOI-correction maneuver (LOI-c) to remove any LOI execution errors



LOI Actual Results

- Segmentation proved well worth the trouble
- Segment 1 was planned using the thrust scale factor from MCC-2
 - Calibration showed the maneuver was 2.5% colder than predicted
- Segment 2 was re-planned using the new thrust scale factor and post-Segment-1 reconstructed/calibrated state
 - Calibration showed this maneuver was 0.7% hot
- Total LOI error
 - Without segmentation, error would have been 2.5% of 166 m/s = 4.2 m/s
 - With segmentation, error was 0.7% of 18 m/s = 0.13 m/s
 - Reduced error by 97%

LOI Correction Maneuver (LOI-c)

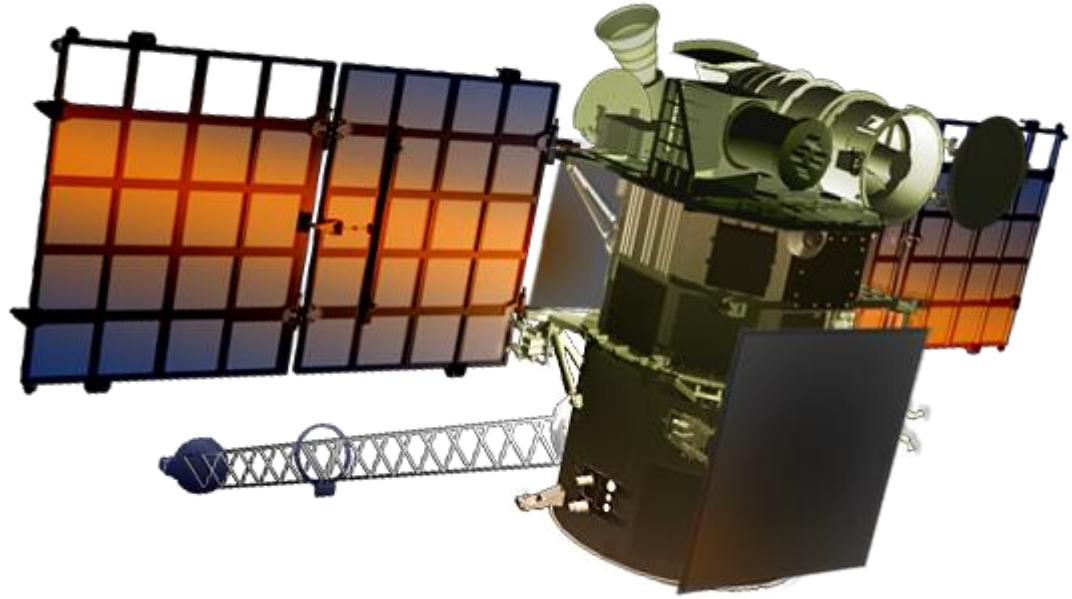
- LOI-c is a stochastic correction maneuver to fine-tune the post-LOI maneuver trajectory
- Planning was similar to a stationkeeping maneuver
 - Stationkeeping maneuver planning for DSCOVR will be discussed in the next talk
 - Chose to execute LOI-c using DSCOVR's -X thruster set
 - Exercised propulsion and attitude control system in this mode for the first time
 - Only opportunity for characterization of on-orbit performance before handover to NOAA
 - Entire ΔV planned along the line of sight from the spacecraft to Earth
 - Allowed spacecraft to stay in science attitude and use high gain antenna for the first time during an orbit maneuver
- DSCOVR LOI-c was relatively small
 - 0.86 m/s ΔV
 - 0.43 kg of hydrazine

Early Operations Conclusions

- Excellent ride and transfer orbit injection by SpaceX Falcon-9
 - Fuel savings for MCC-1 can add years of additional life to the mission
- LOI segmentation reduced maneuver error by 97%
 - Real-time analysis of Segment 1 and re-planning of Segment 2 compensated for initial underburn error within hours
- Maneuver error analyses ensured entire mission operations team was prepared for a wide variety of possible maneuver scenarios
- Communication and planning ensured that maneuvers did not violate any power, thermal, or communications system constraints
- DSCOVR is now collecting science on its Lissajous orbit, with first stationkeeping maneuver not required until early Fall 2015!



Questions?



- Thank you for your attention!